Appendix D

Dose Calculations

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The radiological dose that the public could have received in 1995 from Hanford operations was calculated in terms of the "total effective dose equivalent." The total effective dose equivalent is the sum of the effective dose equivalent from external sources and the committed effective dose equivalent for internal exposure. Effective dose equivalent is a weighted sum of doses to organs and tissues that accounts for the sensitivity of the tissue and the nature of the radiation causing the dose. It is calculated in units of millirem (mrem) (millisievert [mSv])[a] for individuals and in units of person-rem (person-Sv) for the collective dose received by the total population within an 80-km (50-mi) radius of the Site. This appendix describes how the doses in this report were calculated. The values given in this report may be compared to standards for radiation protection (Table C.4, Appendix C).

Releases of radionuclides from Hanford Site activities are usually too low to be measured in offsite air, drinking water, and food crops. Therefore, in most cases, the dose calculations were based on measurements made at the point of release (stacks and effluent streams), and environmental concentrations were estimated from these effluent measurements by environmental transport models.

The transport of radionuclides in the environment to the point of exposure is predicted by empirical models of exposure pathways. These models calculate concentrations of radionuclides in air, water, and foods. Radionuclides taken into the body by inhalation or ingestion may be distributed among different organs and retained for various times. In addition, long-lived radionuclides deposited on the ground become possible sources for long-term external exposure and uptake by agricultural products. Dietary and exposure parameters were applied to calculate radionuclide intakes and radiological doses to the public.

Standardized computer programs were used to perform the calculations. These programs contain internally consistent mathematical models that use site-specific dispersion and uptake parameters. These programs are incorporated in a master code, GENII (Napier et al. 1988a, 1988b, 1988c), which employs the dosimetry methodology described in International Commission on Radiological Protection (ICRP) Reports (1979a, 1979b, 1980, 1981a, 1981b, 1982a, 1982b, 1988). The assumptions and data used in these calculations are described below.

CRITR2 is used for assessment of radiological doses to aquatic organisms and their predators. Both internal and external doses to fish, crustacea, mollusks, and algae, as well as organisms that subsist on them, such as muskrats, raccoons, and ducks may be estimated using CRITR2 (Baker and Soldat 1992).

The computer program, CAP88-PC, was used to calculate dose to a maximally exposed individual as required by 40 CFR 61, Subpart H, from airborne radionuclide effluents (other than radon) released at DOE facilities. Technical details of the CAP88-PC calculations are provided in detail in the 1995 air emissions report (Gleckler et al. 1996).

Types of Dose Calculations Performed

Calculations of radiological doses to the public from radionuclides released into the environment are performed to demonstrate compliance with applicable standards and regulations.

(a) 1 rem (0.01 Sv) = 1,000 mrem (10 mSv).

DOE requires:

- effective dose equivalent to be used in estimating public doses
- biokinetic models and metabolic parameters given by the International Commission of Radiological Protection to be used when estimating doses
- doses to the public to be calculated using facility effluent data, when environmental concentrations are too low to measure accurately.

The calculation of the effective dose equivalent takes into account the long-term (50-year) internal exposure from radionuclides taken into the body during the current year. The effective dose equivalent is the sum of individual committed (50-year) organ doses multiplied by weighting factors that represent the proportion of the total health-effect risk that each organ would receive from uniform irradiation of the whole body. Internal organs may also be irradiated from external sources of radiation. The external exposure received during the current year is added to the committed internal dose to obtain the total effective dose equivalent. In this report, the effective dose equivalent is expressed in rem (or millirem), with the corresponding value in sievert (or millisievert) in parentheses. The numerous transfer factors used for pathway and dose calculations have been documented in GENII (Napier et al. 1988a, 1988b, 1988c) and by Schreckhise et al. (1993).

The following types of radiological doses were estimated:

1. **“Boundary” Dose Rate (mrem/h and mrem/yr)**. The external radiological dose rates during the year in areas accessible by the general public were determined from measurements obtained near operating facilities.

2. **“Maximally Exposed Individual” Dose (mrem)**. The maximally exposed individual is a hypothetical member of the public who lives at a location and has a postulated lifestyle such that it is unlikely that other members of the public would receive higher doses. All potentially significant exposure pathways to this hypothetical individual were considered, including the following:

   - inhalation of airborne radionuclides
   - submersion in airborne radionuclides
   - ingestion of foodstuffs contaminated by radionuclides deposited on vegetation and the ground by both airborne deposition and irrigation water drawn from the Columbia River downstream of the N Reactor
   - exposure to ground contaminated by both airborne deposition and irrigation water
   - ingestion of fish taken from the Columbia River
   - recreation along the Columbia River, including boating, swimming, and shoreline activities.

3. **80-km Population Doses (person-rem)**. Regulatory limits have not been established for population doses. However, evaluation of the collective population doses to all residents within an 80-km (50-mi) radius of Hanford Site operations is required by DOE Order 5400.5. The radiological dose to the collective population within 80 km (50 mi) of the Site was calculated to demonstrate compliance with environmental regulations, confirm adherence to DOE environmental protection policies, and provide information to the public. The 80-km (50-mi) population dose represents the summed products of the individual doses for the number of individuals involved for all exposure pathways.

   Pathways similar to those used for the maximally exposed individual were used to calculate doses to the offsite population. In calculating the effective dose, an estimate was made of the fraction of the offsite population expected to be affected by each pathway. The exposure pathways for the population are as follows:

   - **Drinking Water**. The cities of Richland and Pasco obtain their municipal water directly, and Kennewick indirectly, from the Columbia River downstream from the Hanford Site. A total population of approximately 70,000 in the three cities drinks water derived from the Columbia River.
   - **Irrigated Food**. Columbia River water is withdrawn for irrigation of small vegetable gardens and farms in the Riverview district of Pasco in Franklin County. Enough food is grown in this district to feed an estimated 2,000 people. Commercial crops are also irrigated by Columbia River water in the Horn Rapids area of Benton County. These crops are widely distributed.

- **River Recreation**. These activities include swimming, boating, and shoreline recreation. An estimated 125,000 people who reside within 80 km (50 mi) of the Hanford Site are assumed to be affected by these pathways.

- **Fish Consumption**. Population doses from the consumption of fish obtained locally from the Columbia River were calculated from an estimated total annual catch of 15,000 kg/yr (33,075 lb/yr) (without reference to a specified human group of consumers).

Data

The data that are needed to perform dose calculations based on measured effluent releases include information on initial transport through the atmosphere or river, transfer or accumulation in terrestrial and aquatic pathways, and public exposure. By comparison, radiological dose calculations based on measured concentrations of radionuclides in food require data describing only dietary and recreational activities and exposure times. These data are discussed below.

Population Distribution and Atmospheric Dispersion

Geographic distributions of the population residing within an 80-km (50-mi) radius of the four Hanford Site operating areas are shown in the report *1995 Surface Environmental Surveillance Data* (Bisping 1996). These disributions are based on 1990 Bureau of Census data (Beck et al. 1991). These data influence the population dose by providing estimates of the number of people exposed to radioactive effluents and their proximity to the points of release.

Atmospheric dispersion data are also shown in Bisping (1996). These data describe the transport and dilution of airborne radioactive material, which influences the amounts of radionuclides being transported through the air to specific locations.

Terrestrial and Aquatic Pathways

Important parameters affecting the movement of radionuclides within exposure pathways, such as irrigation rates, growing periods, and holdup periods, are listed in Table D.1. Certain parameters are specific to the lifestyles of either “maximally exposed” or “average” individuals.

Public Exposure

The offsite radiological dose is related to the extent of external exposure to or intake of radionuclides released from Hanford Site operations. Tables D.2 through D.4 give the parameters describing the diet, residency, and river recreation assumed for “maximally exposed” and “average” individuals.

Dose Calculation Documentation

DOE established the Hanford Dose Overview Panel to promote consistency and defensibility of environmental dose calculations at Hanford. The Hanford Dose Overview Panel has the responsibility for defining standard, documented computer codes and input parameters to be used for radiological dose calculations for the public in the vicinity of the Hanford Site. Only those procedures, models, and parameters previously defined by the Hanford Dose Overview Panel were used to calculate the radiological doses (Schreckhise et al. 1993). The calculations were then reviewed by the Dose Overview Panel. Summaries of dose calculation technical details for this report are shown in Tables D.5 through D.9 and in the report *1995 Surface Environmental Surveillance Data* (Bisping 1996).

Table D.1. Food Pathway Parameters Used in Dose Calculations, 1995

	Holdup, days[a]				
	Maximally Exposed Individual	Average Individual	Growing Period, days	Yield, kg/m^2	Irrigation Rate, L/m^2/month
Leafy vegetables	1	14	90	1.5	150
Other vegetables	5	14	90	4	170
Fruit	5	14	90	2	150
Cereal	180	180	90	0.8	0
Eggs	1	18	90	0.8	0
Milk	1	4			
Hay	(100)[b]	(100)	45	2	200
Pasture	(0)	(0)	30	1.5	200
Red meat	15	34			
Hay	(100)	(100)	45	2	200
Grain	(180)	(180)	90	0.8	0
Poultry	1	34	90	0.8	0
Fish	1	1	--	--	--
Drinking water	1	1	--	--	--

(a) Holdup is the time between harvest and consumption.
(b) Values in ( ) are the holdup in days between harvest and consumption by farm animals.

Table D.2. Dietary Parameters Used in Dose Calculations, 1995

	Consumption, kg/yr	
	Maximally Exposed Individual	Average Individual
Leafy vegetables	30	15
Other vegetables	220	140
Fruit	330	64
Grain	80	72
Eggs	30	20
Milk[a]	270	230
Red meat	80	70
Poultry	18	8.5
Fish	40	--[a]
Drinking water[b]	730	440

(a) Average individual consumption not identified; radiation doses were calculated based on estimated total annual catch of 15,000 kg (33,075 lb).
(b) Units L/yr.

Table D.3. Residency Parameters Used in Dose Calculations, 1995

Parameter	Exposure, h/yr Maximally Exposed Individual	 Average Individual
Ground contamination	4,383	2,920
Air submersion	8,766	8,766
Inhalation[a]	8,766	8,766

(a) Inhalation rates: Adult 270 cm^3/s.

Table D.4. Recreational Parameters Used in Dose Calculations, 1995

Parameter	Exposure, h/yr[a] Maximally Exposed Individual	 Average Individual
Shoreline	500	17
Boating	100	5
Swimming	100	10

(a) Assumed river water travel times from 100-N to the point of aquatic recreation were 8 h for the maximally exposed individual and 13 h for the average individual. Correspondingly lesser times were used for other locations.

Table D.5. Technical Details of 100 Areas Airborne Release Dose Calculations, 1995

Facility name	100-N Area
Releases	See Table 3.1.1
Meteorological conditions	1995 annual average, calculated from data collected at the 100-N Area and the Hanford Meteorology Station from January 1995 through December 1995, using the computer code HANCHI
$\overline{X}/Q'$	Maximally Exposed Individual at residence, 4.2 x 10^{-9} s/m^3 at 41 km SE; Maximally Exposed Individual at food source, 2.9 x 10^{-9} s/m^3 at 53 km SSE; 80-km population, 1.0 x 10^{-3} s/m^3 person-s/m^3
Release height	10-m effective stack height
Population distribution	375,000 (see Table D-1, Bisping [1996])
Computer code	GENII, Version 1.485, 12-3-90
Doses calculated	Chronic, 1-year exposure, 50-year committed internal dose equivalent, and annual effective dose equivalent to individual and population
Pathways considered	External exposure to plume and ground deposits Inhalation Ingestion of locally produced foods
Files addressed	Radionuclide Library, Rev. 7-1-92 Food Transfer Library, Rev. 8-29-88 External Dose Factor Library, Rev. 5-9-88 Internal Dose Factor Library, Rev. 12-3-90

Table D.6. Technical Details of 100-N Area Liquid Release Dose Calculations, 1995

Facility name	100-N Area
Releases	See Table 3.1.4
Mean river flow	113,075 ft^3/s (3,200 m^3/s)
Shore-width factor	0.2
Population distribution	70,000 for drinking water pathway 125,000 for aquatic recreation 2,000 for consumption of irrigated foodstuffs 15,000 kg/yr total harvest of Columbia River fish
Computer code	GENII, Version 1.485, 12-3-90
Doses calculated	Chronic, 1-year exposure, 50-year committed internal dose equivalent, and annual effective dose equivalent to individual and population
Pathways considered	External exposure to irrigated soil, to river water, and to shoreline sediments Ingestion of aquatic foods, and irrigated farm products
Files addressed	Radionuclide Library, Rev. 7-1-92 Food Transfer Library, Rev. 8-29-88 External Dose Factor Library, Rev. 5-9-88 Internal Dose Factor Library, Rev. 12-3-90 Bioaccumulation Factor Library, Rev. 10-26-92

Table D.7. Technical Details of 200 Areas Airborne Release Dose Calculations, 1995

Facility name	200 Areas
Releases	See Table 3.1.1
Meteorological conditions	1995 annual average, calculated from data collected at the Hanford Meteorology Station from January 1995 through December 1995, using the computer code HANCHI
$\overline{X}$/Q’	Maximally Exposed Individual at residence, 1.2 x 10^{-8} s/m^3 at 34 km SE; Maximally Exposed Individual at food source, 8.7 x 10^{-9} s/m^3 at 45 km SE; 80-km population, 1.5 x 10^{-3} person-s/m^3
Release height	89-m effective stack height
Population distribution	376,000 (see Table D-2, Bisping [1996])
Computer code	GENII, Version 1.485, 12-3-90
Doses calculated	Chronic, 1-year exposure, 50-year committed internal dose equivalent, and annual effective dose equivalent to individual and population
Pathways considered	External exposure to plume and ground deposits Inhalation Ingestion of locally produced foods
Files addressed	Radionuclide Library, Rev. 7-1-92 Food Transfer Library, Rev. 8-29-88 External Dose Factor Library, Rev. 5-9-88 Internal Dose Factor Library, Rev. 12-3-90

Table D.8. Technical Details of 300 Area Airborne Release Dose Calculations, 1995

Facility name	300 Area
Releases	See Table 3.1.1
Meteorological conditions	1995 annual average, calculated from data collected at the 300 Area and the Hanford Meteorology Station from January 1995 through December 1995, using the computer code HANCHI
$\overline{X}/Q'$	Maximally Exposed Individual at residence, 8.8 x 10^{-7} s/m^3 at 1.5 km E; Maximally Exposed Individual at food source, 8.5 x 10^{-8} s/m^3 at 13 km SSE; 80-km population, 6.5 x 10^{-3} person-s/m^3
Release height	10 m
Population distribution	282,000 (see Table D-3, Bisping [1996])
Computer code	GENII, Version 1.485, 12-3-90
Doses calculated	Chronic, 1-year exposure, 50-year committed internal dose equivalent, and annual effective dose equivalent to individual and population
Pathways considered	External exposure to plume and ground deposits Inhalation Ingestion of locally produced foods
Files addressed	Radionuclide Library, Rev 7-1-92 Food Transfer Library, Rev. 8-29-88 External Dose Factor Library, Rev. 5-9-88 Internal Dose Factor Library, Rev. 12-3-90

Table D.9. Technical Details of 400 Area Airborne Release Dose Calculations, 1995

Facility name	400 Area
Releases	See Table 3.1.1
Meteorological conditions	1995 annual average, calculated from data collected at the 400 Area and the Hanford Meteorology Station from January 1995 through December 1995, using the computer code HANCHI
$\overline{X}/Q'$	Maximally Exposed Individual at residence, 9.9 x 10^{-8} s/m^3 at 11 km SE; Maximally Exposed Individual at food source, 3.2 x 10^{-8} s/m^3 at 23 km SSE; 80-km population, 4.9 x 10^{-3} person-s/m^3
Release height	10 m
Population distribution	283,000 (see Table D-4, Bisping [1996])
Computer code	GENII, Version 1.485, 12-3-90
Doses calculated	Chronic, 1-year exposure, 50-year committed internal dose equivalent, and annual effective dose equivalent to individual and population
Pathways considered	External exposure to plume and ground deposits Inhalation Ingestion of locally produced foods
Files addressed	Radionuclide Library, Rev 7-1-92 Food Transfer Library, Rev. 8-29-88 External Dose Factor Library, Rev. 5-9-88 Internal Dose Factor Library, Rev. 12-3-90

Table D.10. Annual Dose to Workers in the 400 Area from Ingestion of Drinking Water Obtained from Ground-Water Wells

Radionuclide	Drinking Water Concentration (pCi/L)[(a)]	Intake (Bq/yr)[(b)]	Ingestion Dose Factor (Sv/Bq)[(c)]	Ingestion Dose (Sv/yr)[rem/yr]
Total Alpha[(d)]	0.12 ± 0.44	1.1	7.66×10^{-8}	8.2×10^{-8} [8.2×10^{-6}]
Total Beta[(e)]	6.72 ± 1.82	6.0	1.35×10^{-8}	8.1×10^{-7} [8.1×10^{-5}]
Tritium	8,424 ± 304	75,000	1.73×10^{-11}	1.3×10^{-6} [1.3×10^{-4}]
^{90}Sr	0.004 ± 0.006	0.036	3.85×10^{-8}	1.4×10^{-9} [1.4×10^{-7}]
^{129}I	0.0095 ± 0.001	0.0084	7.46×10^{-8}	6.3×10^{-9} [6.3×10^{-7}]
Total				2.2×10^{-6} [2.2×10^{-4}]

(a) Drinking water concentrations are annual average concentrations obtained from monthly samples taken during 1995 (see Table 4.3.2).
(b) Intake is based on the assumption that a worker ingests 1 L/day of ground water during the entire working year (taken to be 240 days for the analysis). 1 Ci = 3.7×10^{10} Bq.
(c) Ingestion intake-to-dose conversion factors are taken from Eckerman et al. (1988). Where the document lists dose factors for more than one chemical form of a radionuclide, the most soluble chemical form was assumed.
(d) Total alpha concentrations were assumed to be ^{234}U for the purposes of this analysis.
(e) Total beta concentrations were assumed to be ^{137}Cs for the purposes of this analysis.

References

Beck, D. M., and B. A. Napier, M. J. Scott, A. G. Thurman, M. D. Davis, D. B. Pittenger, S. F. Shindle, andN. C. Batishko. 1991. *Hanford Area 1990 Population and 50-Year Projections.* PNL-7803, Pacific Northwest Laboratory, Richland, Washington.

Bisping, L. E. 1996. *Hanford Site Environmental Data for Calendar Year 1995—Surface and* C*olumbia River*. PNL-XXXXX, Pacific Northwest National Laboratory, Richland, Washington.

DOE Order 5400.5. "Radiation Protection of the Public and the Environment."

Eckerman, K. F., A. B. Wolbarst, and A. C. B. Richardson. 1988. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion. Federal Guidance Report No. 11*. EPA/520/1-88-020, Office of Radiation Programs, U.S. Environmental Protection Agency, Washington, D.C.

Gleckler, B. P., L. P. Diediker, K. Rhoads, E. G. Damberg, and S. J. Jette. 1996. Radionuclide Air Emissions Report for the Hanford Site Calendar Year 1995. DOE/RL-96-37, U.S. Department of Energy, Richland, Washington.

International Commission on Radiological Protection (ICRP). 1979a. *ICRP Publication 30, Part 1, Limits for Intakes of Radionuclides by Workers.* Annals of the ICRP, Vol. 2, No. 3/4. Pergamon Press, Elmsford, New York.

International Commission on Radiological Protection (ICRP). 1979b. *ICRP Publication 30, Supplement to Part 1, Limits for Intakes of Radionuclides by Workers.* Annals of the ICRP, Vol. 3, No. 1-4, Pergamon Press, Elmsford, New York.

International Commission on Radiological Protection (ICRP). 1981a. *ICRP Publication 30, Supplement to Part 2, Limits for Intakes of Radionuclides by Workers.* Annals of the ICRP, Vol. 5, No. 1-6, Pergamon Press, Elmsford, New York.

International Commission on Radiological Protection (ICRP). 1981b. *ICRP Publication 30, Part 3 Including Addendum to Parts 1 and 2, Limits for Intakes of Radionuclides by Workers*. Annals of the ICRP, Vol. 6, No. 2/3, Pergamon Press, Elmsford, New York.

International Commission on Radiological Protection (ICRP). 1982a. *ICRP Publication 30, Supplement A to Part 3, Limits for Intakes of Radionuclides by Workers.* Annals of the ICRP, Vol. 7, No. 1-3, Pergamon Press, Elsmford, New York.

International Commission on Radiological Protection (ICRP). 1982b. *ICRP Publication 30, Supplement B to Part 3 Including Addendum to Supplements to Parts 1 and 2, Limits for Intakes of Radionuclides by Workers.* Annals of the ICRP, Vol. 8, No. 1-3, Pergamon Press, Elmsford, New York.

International Commission on Radiological Protection (ICRP). 1988. *ICRP Publication 30, Part 4, Limits for Intakes of Radionuclides by Workers: an Addendum.* Annuals of the ICRP, Vol. 19, No. 4, Pergamon Press, Elmsford, New York.

Napier, B. A., R. A. Peloquin, D. L. Strenge, and J. V. Ramsdell. 1988a. *Conceptual Representation. Volume 1 of GENII - The Hanford Environmental Radiation Dosimetry Software System.* PNL-6584, Vol. 1, Pacific Northwest Laboratory, Richland, Washington.

Napier, B. A., R. A. Peloquin, D. L. Strenge, and J. V. Ramsdell. 1988b. *User's Manual. Volume 2 of GENII - The Hanford Environmental Radiation Dosimetry Software System.* PNL-6584, Vol. 2, Pacific Northwest Laboratory, Richland, Washington.

Napier, B. A., R. A. Peloquin, D. L. Strenge, and J. V. Ramsdell. 1988c. *Code Maintenance Manual. Volume 3 of GENII - The Hanford Environmental Radiation Dosimetry Software System.* PNL-6584, Vol. 3, Pacific Northwest Laboratory, Richland, Washington.

Schreckhise, R. G., K. Rhoads, J. S. Davis, B. A. Napier, and J. V. Ramsdell. 1993. *Recommended Environmental Dose Calculation Methods and Hanford-Specific Parameters*. PNL-3777 Rev. 2, Pacific Northwest Laboratory, Richland, Washington.